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AN INVESTIGATION OF THE ACOUSTIC ENERGY OF UNDERWATER EXPLOSIONS OF GASEOUS HYDROGEN AND OXYGEN IN A GAS-WATER RESONATOR

JAMES F. MILES
and
JULIAN C. PATRICK, JR.

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AN INVESTIGATION OF THE ACOUSTIC ENERGY OF UNDERWATER EXPLOSIONS OF GASEOUS HYDROGEN AND OXYGEN IN A GAS-WATER RESONATOR

[redacted]

* * * * *

James F. Miles

and

Julian C. Patrick, Jr.

AN INVESTIGATION OF THE ACOUSTIC ENERGY OF UNDERWATER EXPLOSIONS OF GASEOUS HYDROGEN AND OXYGEN IN A GAS-WATER RESONATOR

by

James F. Miles

Lieutenant Commander, Royal Canadian Navy

and

Julian C. Patrick, Jr.

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

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M58513~~

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This work is accepted as fulfilling
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MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS
from the
United States Naval Postgraduate School

ABSTRACT

In recent years at the U. S. Naval Postgraduate School, a great deal of interest has been exhibited in the use of hydrogen-oxygen explosions in semi-enclosed chambers as an underwater acoustic signal source. The basic intent of this thesis was an investigation of the amount of acoustic energy available from such a controlled explosion and its dependence on various mixtures of gas, including excess amounts of hydrogen, oxygen and nitrogen.

The low energy yields obtained were both unexpected and disappointing and the efficiency of conversion from chemical to acoustic energy was astonishingly low; so low that the value of the process as a source of acoustic signals is considered to be of doubtful significance.

Frequency spectra and time domain photographs of each explosion and a short section on variation of energy with depth of explosion are included.

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1. Introduction.

This thesis was undertaken as a direct follow-up of some of the recommendations made in theses completed at the Naval Postgraduate School in 1960 and 1961. /1/, /2/

Since the work done in these theses indicated that explosive mixtures of oxygen and hydrogen could be obtained by controlled electrolysis in sea water and that a judicious choice of chamber size and shape, explosive mixture, quantity and type of excess gas and depth could result in acoustic signals of discrete bandwidth, it was felt by the authors that further investigation of this method of generating acoustic signals could yield important results.

The authors decided that the field of acoustic energy measurement was most important since it would lead to a knowledge of the actual acoustic energy available and to a determination of the chemical to acoustic energy conversion efficiency. In addition, this area of study would provide a method of determining the most efficient mixture, the best shape of transducer and any changes in mixture which might be required, as a function of depth, to maintain efficiency.

Due to problems encountered in the calibration of hydrophones, in devising a method of positioning the hydrophone with respect to the transducer without inducing secondary effects in the system and, in no small degree, to poor weather conditions over a large part of the period available for experimentation, it was not possible to investigate all of these parameters. Since a simple transducer was available from previous experiments, /2/, it was used in this experiment with the intention of modifying it as results and developments dictated. Due to the problems previously mentioned, no changes were made and the results presented in this thesis

are for this transducer only.

In conducting the experiments, a hydrophone was connected to a tape recorder which received and stored the signal for later analysis in the laboratory. Analysis was carried out using a spectrum analyzer and oscilloscope for frequency and time domain studies. The acoustic energy was calculated by a time sampling technique with voltage ordinates obtained from the expanded trace of the memoscope and converted to pressure ordinates through a knowledge of the characteristics of the hydrophone and tape recorder. The equipment, the techniques used, and the calibration procedures followed are more fully discussed in the Appendices.

It would not be possible here to include the names of all who have been of assistance to us in obtaining equipment and providing guidance and advice. We do, however, wish to extend our thanks to Professor C. F. Klamm for assistance with the energy calculation method, to Professors L. E. Kinsler, O. B. Wilson and D. A. Stentz for helpful suggestions, to Professor C. E. Mennecken for arranging the loan of the spectrum analyzer, and to the First Lieutenant, LCDR W. E. Walkup, who provided the boat and crew without which it would not have been possible to conduct the experiments. Special thanks go to the men of the boat crew and technicians of the electronics staff who worked for us under sometimes adverse conditions at sea.

2. Equipment and Measurements

(a) Transducer, Gas Measurement and Ignition of Explosion

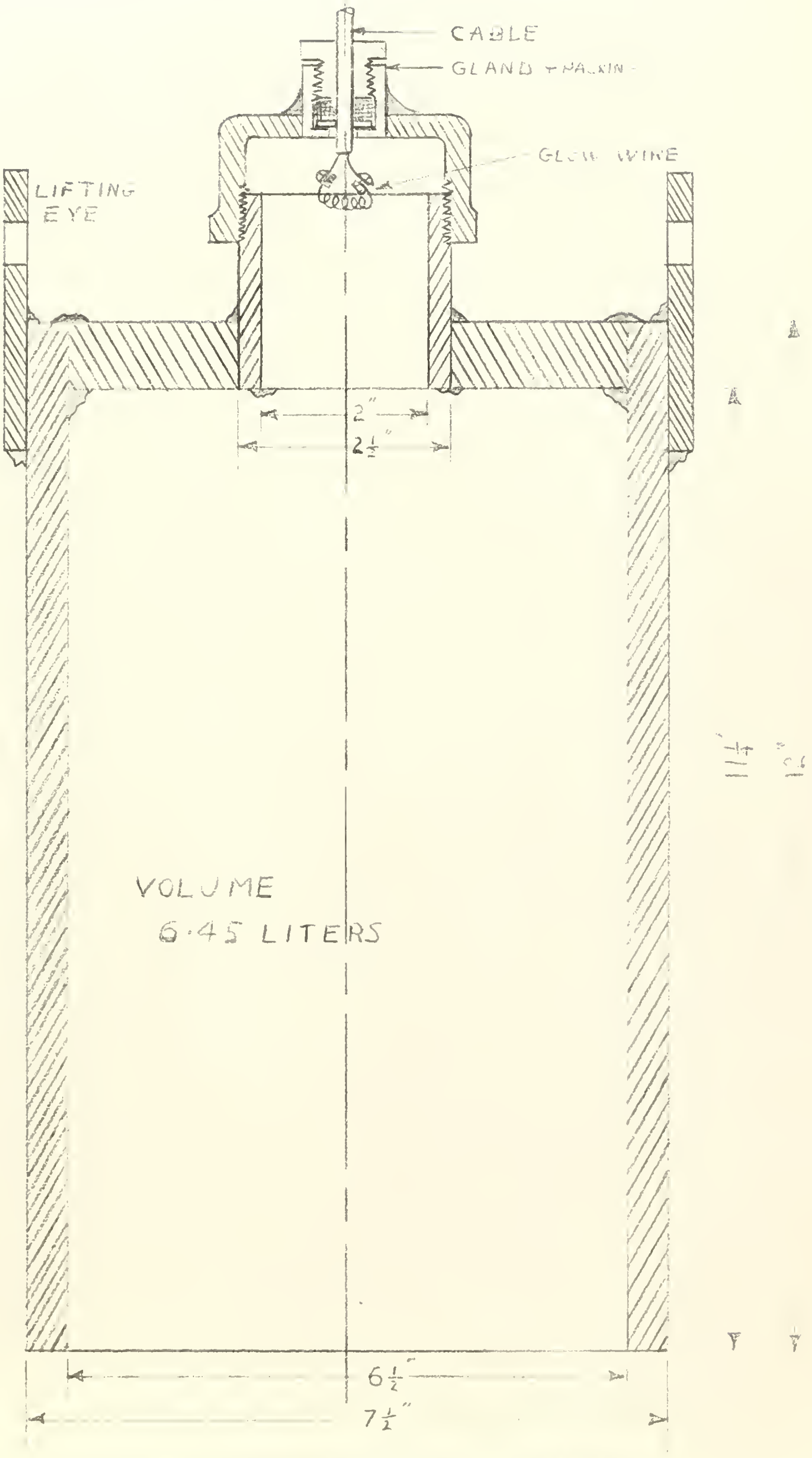
As mentioned, the explosive chamber (transducer) was available from previous experiments. /2/ The transducer is shown in Fig. 1.

The gas volume measurement procedure used was identical with that employed by previous experimenters /2/ and the calibration curves for the regulator valves used are given in Appendix I.

Ignition of the explosion was accomplished by placing two six volt d.c. batteries in series across a resistance coil in the explosive chamber. Firing current varied from 10 to 12 amperes. Ignition time varied from 8 to 20 sec and seemed to be an increasing function of the amount of excess gas.

(b) Hydrophone

The hydrophone used was a BICR3a for which a calibration curve was available from 40 cps to 600 cps when used with 35 ft of 2 conductor shielded cable. Since an additional 200 ft of cable had to be added to this short cable to reach the depths at which the tests were conducted, reciprocity calibrations were attempted, in a tank, at several frequencies between 50 and 600 cps. As might be expected, difficulties were encountered with standing waves and accurate results were not obtained. However, with the results that were obtained and by comparison through the substitution method with an M115B hydrophone, for which a calibration curve was available, a figure of -35 db re 1 volt per microbar was obtained for the frequency range of interest. This compared with -81.5 db re 1 volt per microbar given on the calibration curve and seems entirely reasonable in view of the extra length of cable involved. This figure of -85 db re 1 volt per microbar was used as the hydrophone response in



SKETCH OF TRANSDUCER USED - FIGURE 1

all calculations.

(c) Hydrophone Positioning

In measuring the acoustic energy available from an explosion it is necessary to fix the hydrophone at a known distance from the source of the explosion. It is also important to know whether there is any directionality in the propagation of the sound due to the transducer configuration or other factors. If measurements could be made at several fixed angles relative to the transducer while maintaining a fixed distance from it, any directionality present in the signal should be apparent. An attempt was made to meet these requirements by fixing the hydrophone to the end of a boom, the other end of which was pivoted at the suspension point of the transducer.

Unfortunately, it was found that with a free hanging transducer, as was used in these experiments, the presence of the boom had an effect on the explosion and that this effect varied with the position of the boom. For instance, high frequencies (3-4 Kcs.) were observed in the output when the boom was vertical or close to vertical which were not present when the hydrophone was placed in the same position by tying it to the suspension line and removing the boom. This indicated that the boom was excited to longitudinal vibration by the force of the explosion and that the high frequencies came from the boom and not the transducer. The boom was therefore discarded and another approach to the problem of directionality was made.

The hydrophone was attached to a length of line which was secured to the suspension cable of the transducer; sufficient tension was placed on the hydrophone cable to insure that the hydrophone to transducer spacing was approximately the length of the line. In this way the hydrophone was positioned at several different though unknown angles with respect to the transducer. When the output wave forms of explosions with the hydrophone directly

above the transducer were compared with the output wave forms of similar explosions with the hydrophone approximately the same distance to one side of the transducer, they were found to be quite similar and, with few exceptions, contained no frequencies above 600 cps. Since it is known that little directivity can be expected from any device whose physical dimensions are less than one quarter wave length, (approx. 100 inches at 600 cps in sea water) it was apparent that the 7-1/2 inches diameter by 18 inches long transducer could not direct the sound. On this premise, the transducer was treated as a point source, radiating sound uniformly in all directions, and all measurements were made with the hydrophone secured to the transducer suspension line at a point 20 ft above the center of the transducer.

(d) Recording System

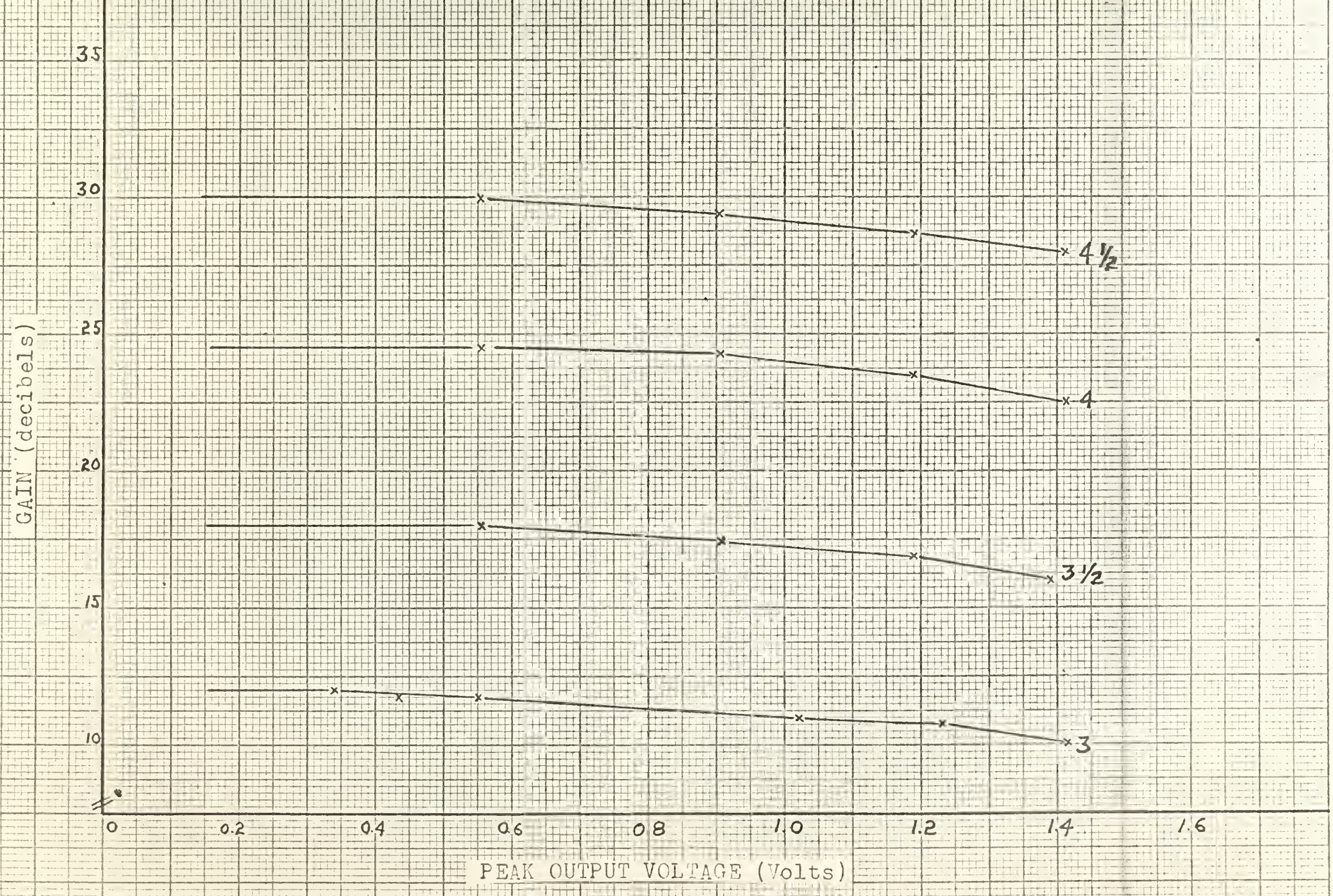
Since an open boat without an electric power plant was employed as a platform from which to conduct the actual explosions in deep water, it was not possible to take analysis equipment along. Instead, a small 12 volt d.c. to 117 volt 60 cps rotary converter was used to supply an Ampex 600 Tape Recorder, on which all explosions were recorded.

The tape recorder had a relatively small dynamic range (about 25 db) and care had to be taken not to overload the input amplifier. Whenever overload did occur, the shot was repeated at a lower input level. Tape recorder gain characteristics were investigated as a function of input level and are given in Fig. 2. In all calculations gains of 12, 18, and 24 db we were used for microphone input levels of 3.0, 3.5 and 4.0 respectively.

(e) Analysis

Analysis of the recorded explosion waveforms was carried out in both the time and frequency domains. The output of the tape recorder, properly terminated in a 600 ohm load, was fed to a Hughes "Memoscope"

FIGURE NO. 2
TAPE RECORDER GAIN CHARACTERISTICS
MICROPHONE INPUT LEVEL AS PARAMETER.



in order to obtain voltage vs time waveforms which could be converted to pressure vs time through a knowledge of the tape recorder and hydrophone response characteristics.

Using sampling theory, it was possible to calculate the acoustic energy generated by each explosion from the pressure vs time waveforms. Appendix II gives the theory and an illustration of the technique used in these calculations.

The output of the tape recorder was also fed to a Kay Electric "Vibralyzer" from which an amplitude vs frequency spectrum was obtained, usually from 5 to 250 cps but occasionally 5 to 500 cps when the spectrum spread beyond 250 cps. It was not possible to calibrate the Vibralyzer so as to give absolute intensity levels, due to the complicated interaction of the record level, reproduce level and mark level controls but relative amplitudes of prominent components could be determined. The amplitude scales on the spectra in Appendix IV are therefore plotted in db below the amplitude of the peak component.

It may be noted in many of the time domain photographs, most noticeably in number 22, that a high frequency component is present during portions of the output pulse. The frequency of this component was determined to be about 2 Kcs which is the frequency of "ringing" of the transducer itself when partially filled with gas, suspended just below the surface and hit with a hammer. Since this component is insignificant in nearly all cases, it was ignored in computing the energy content of the output waveforms.

3. Results

At the beginning of the investigation, it was known /2/ that the amount of gas in the chamber over and above the amount that would recombine in the explosion was one of the factors controlling the width of the spectrum that would be obtained. It was also implied, if not stated, that the acoustic energy available from the explosions in the transducer was quite large. /1/ This assumption was later proven to be invalid; but the investigation began with it as a basis with the intent of measuring this energy, investigating any directionality of the transducer as a necessary adjunct to measuring the energy and computing the chemical to acoustical energy conversion efficiency.

As the investigation progressed, results were obtained which indicated that not only the amount of excess gas but, to some extent, the nature of the excess gas was a parameter affecting the acoustic energy content of the explosion. The authors decided at this point to concentrate their efforts in this area and to attempt to determine as nearly as possible the mixture at one depth which would produce the maximum acoustic energy.

A transducer depth of 200 ft and a water depth always in excess of 400 ft were selected to minimize surface and bottom reflections. Numerous explosions were set off with varying amounts of pure hydrogen, oxygen and nitrogen as the excess gas and additional shots were made with various mixtures of these gases as excess. During this series of shots, one liter of combustible mixture (0.33 liter O_2 and 0.67 liter H_2) was maintained.

The end results of the investigation can best be appreciated from a study of Figures 3, 4, and 5, which show curves of acoustic energy as a function of quantity of excess gas for pure hydrogen excess, pure nitrogen excess, and various mixtures of excess respectively. It is immediately

obvious that the addition of excess gas affects the acoustic output and that peak acoustic output occurs for ratios of excess gas to explosive mixture between 1.5:1 and 2:1. This peaking effect correlates to some extent with detonation velocities for mixtures of these same gases given on page 80, Underwater Explosions by R. H. Cole /3/.

The most surprising result of the investigation, was neither that a peak did occur nor that it occurred where it did, but that the acoustic output at this peak was so small. When it is considered that over 7000 joules of free energy is available in the recombination of the gases involved, (see Appendix IV) the conversion of less than one joule to acoustic energy given a conversion efficiency in the neighborhood of 1/100 of one percent. When it is further considered that the spectra obtained in the region of maximum efficiency are relatively broad compared to the narrower spectra obtained with less efficient explosions, it is apparent that the requirements of high acoustic output and narrow spectrum are mutually incompatible, at least for the particular transducer used in these tests. In any case the very low acoustic efficiency indicates the process is of doubtful value as a source of high intensity acoustic signals.

Although the study of the spectra involved in these explosions has already been well covered /2/, the time domain pictures, frequency spectra and a tabulation of acoustic energy content are included in Appendix III for those interested in studying them. Time domain pictures have ordinates converted to pressure in newtons/meter^2 and abscissa given in milli-seconds, while the frequency spectra ordinates give relative power in decibels below the power in the strongest frequency component.

A brief study of acoustic energy as a function of depth was attempted. For a single mixture, shots were conducted at 200, 175, 150, 125, and 100

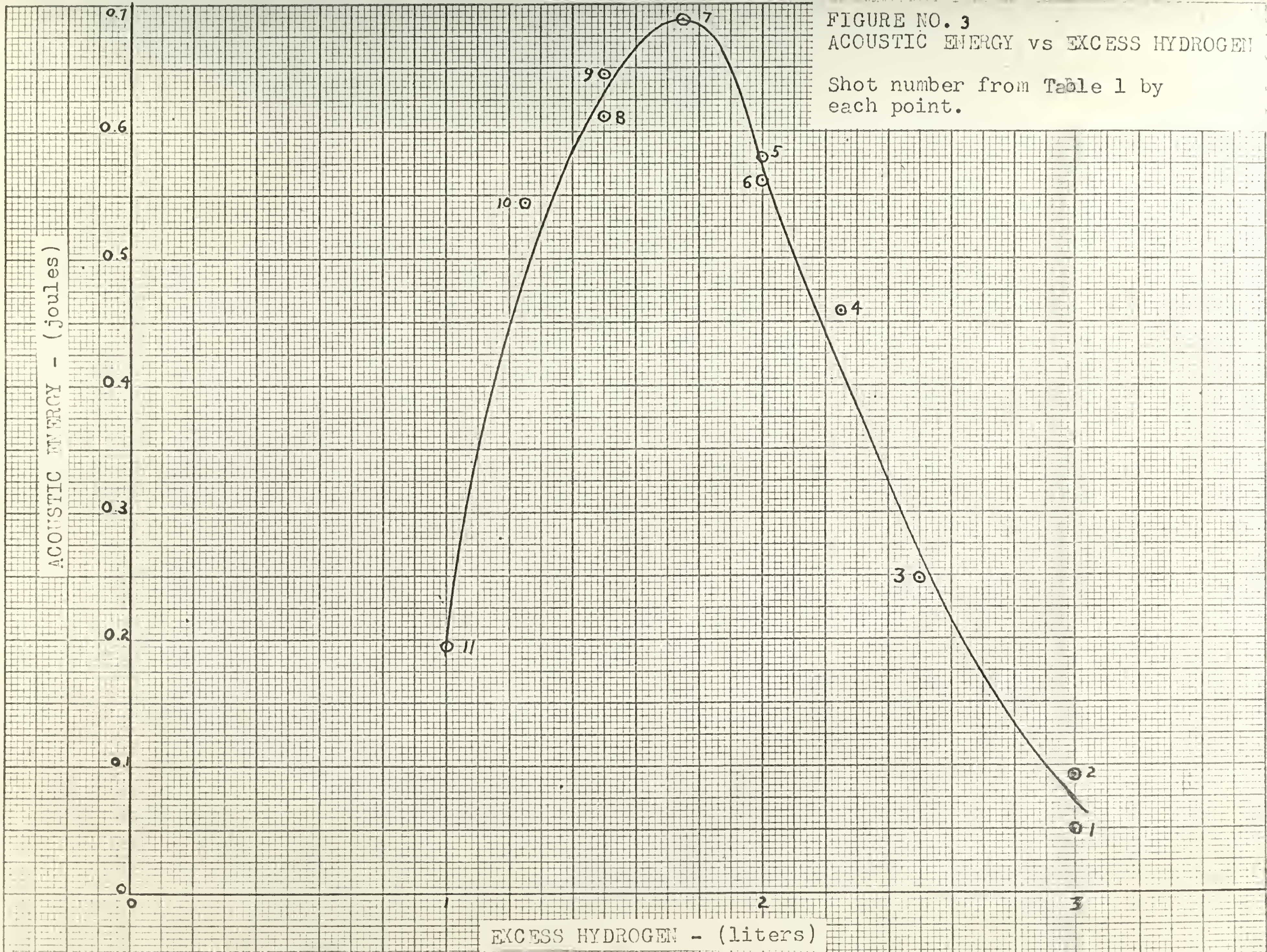
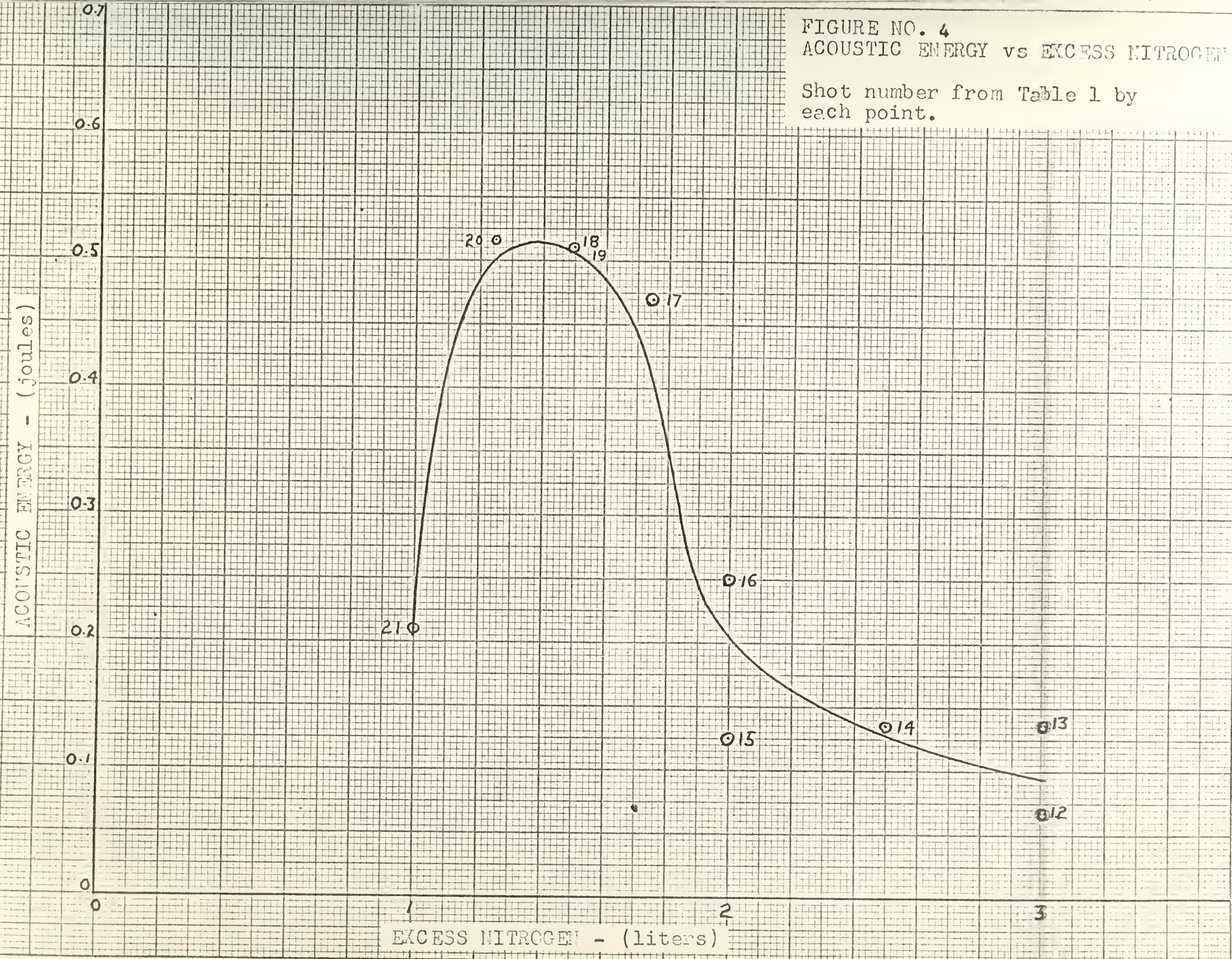


FIGURE NO. 3
ACOUSTIC ENERGY vs EXCESS HYDROGEN

Shot number from Table 1 by each point.

FIGURE NO. 4
ACOUSTIC ENERGY vs EXCESS NITROGEN

Shot number from Table 1 by each point.



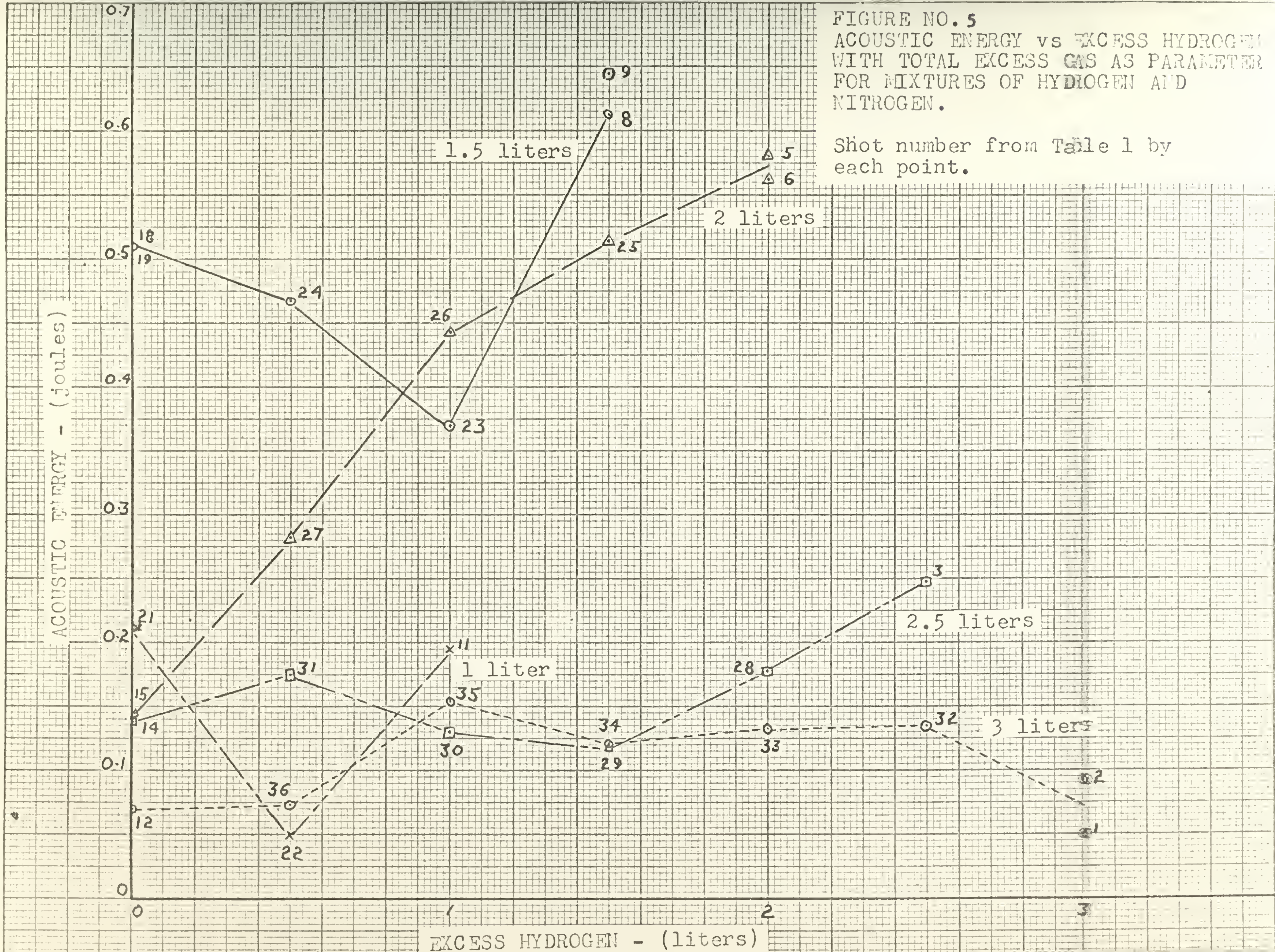


FIGURE NO. 5
ACOUSTIC ENERGY vs EXCESS HYDROGEN WITH TOTAL EXCESS GAS AS PARAMETER FOR MIXTURES OF HYDROGEN AND NITROGEN.

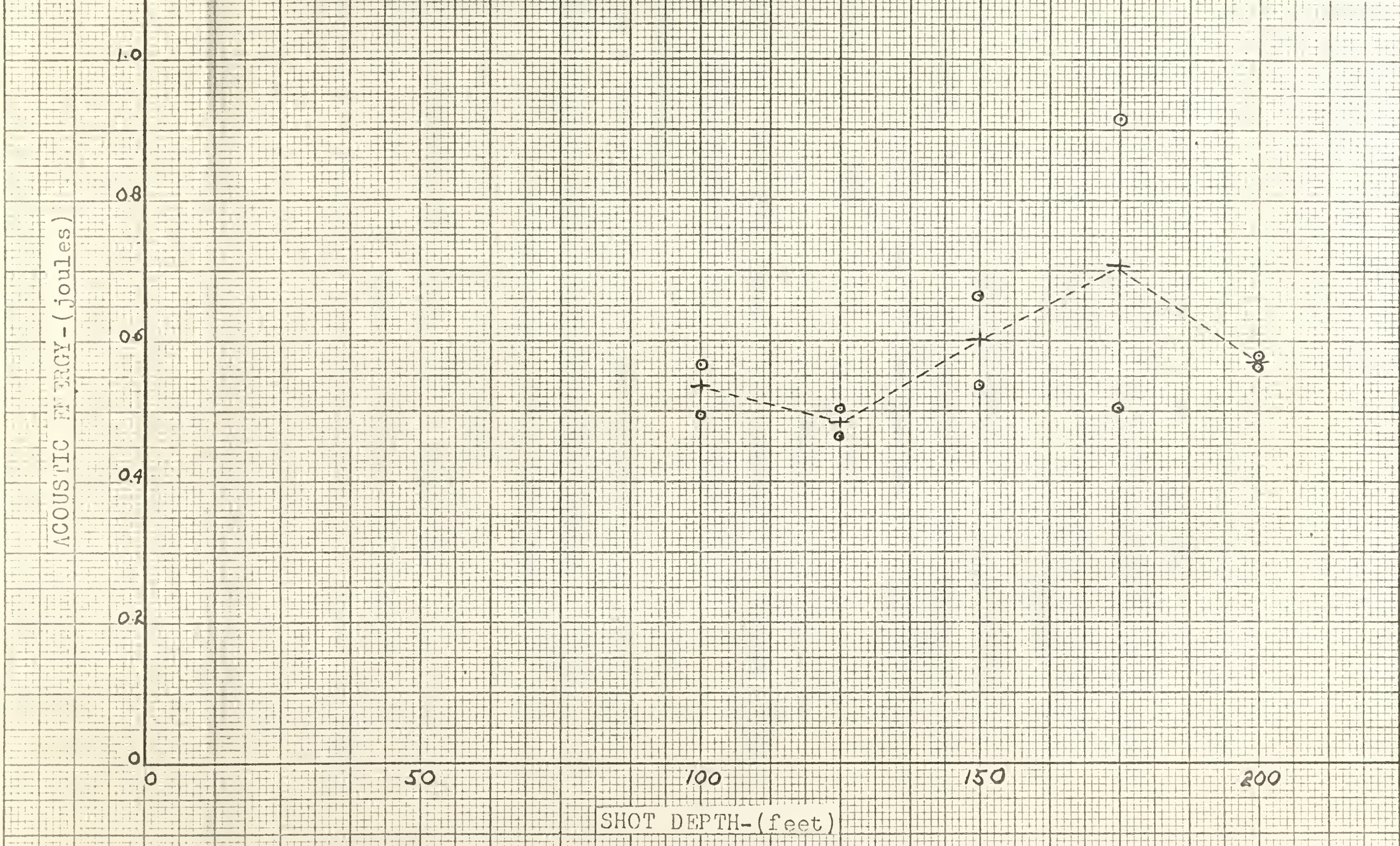
Shot number from Table 1 by each point.

feet. The mixture chosen had two liters excess hydrogen and the results are plotted in Fig. 6 which indicates that there is no significant variation over the range of depths investigated.

Interesting, though not important, results were obtained in the explosions which contained oxygen as the excess gas (Appendix IV), numbers 37 to 41). The pulse was approximately the same pressure level as the excess hydrogen and nitrogen shots, but was of very short duration, in some cases only one or two cycles of oscillation.

FIGURE NO. 6

VARIATION OF ENERGY WITH DEPTH.
(All shots--2 liters excess hydrogen)
Average of two shots at each depth
joined by dotted line.



4. Conclusions.

(a) Acoustic energy content is a function of excess gas in the explosive mixture and varies with the nature of the excess gas.

(b) As a function of the amount of excess gas, the range over which maximum acoustic energy is obtained does not correspond with the range over which the narrow bandwidth desired is obtained. Therefore, for the transducer used, these two desirable characteristics are incompatible.

(c) Chemical to acoustic energy conversion efficiencies are extremely low in the transducer used in these experiments. Peak efficiency obtained was of the order of 1/100 of one percent.

(d) The efficiency of the process, using bottled gas or in conjunction with a hydrolysis process, is so low that its value as a source of high intensity acoustic signals is extremely doubtful.

5. Recommendations.

(a) No further work should be done in this field at the U. S. Naval Postgraduate School unless theoretical studies indicate a transducer design, gas mixture or detonation method which would improve the conversion efficiency by at least 3 orders of magnitude.

(b) In the event that further work is authorized, a more suitable boat with an internal power supply and equipped with suitable power winches should be provided as a platform from which to conduct the tests.

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APPENDIX I

GAS VOLUME MEASUREMENTS

The technique of metering the gas into the explosive chamber was developed by previous experimenters. /2/ The calibration curves for the regulator valves used are shown in Fig. 7 where the ordinate is milli-liters of gas and the abscissa is gas pressure in the high pressure gauge of the valve.

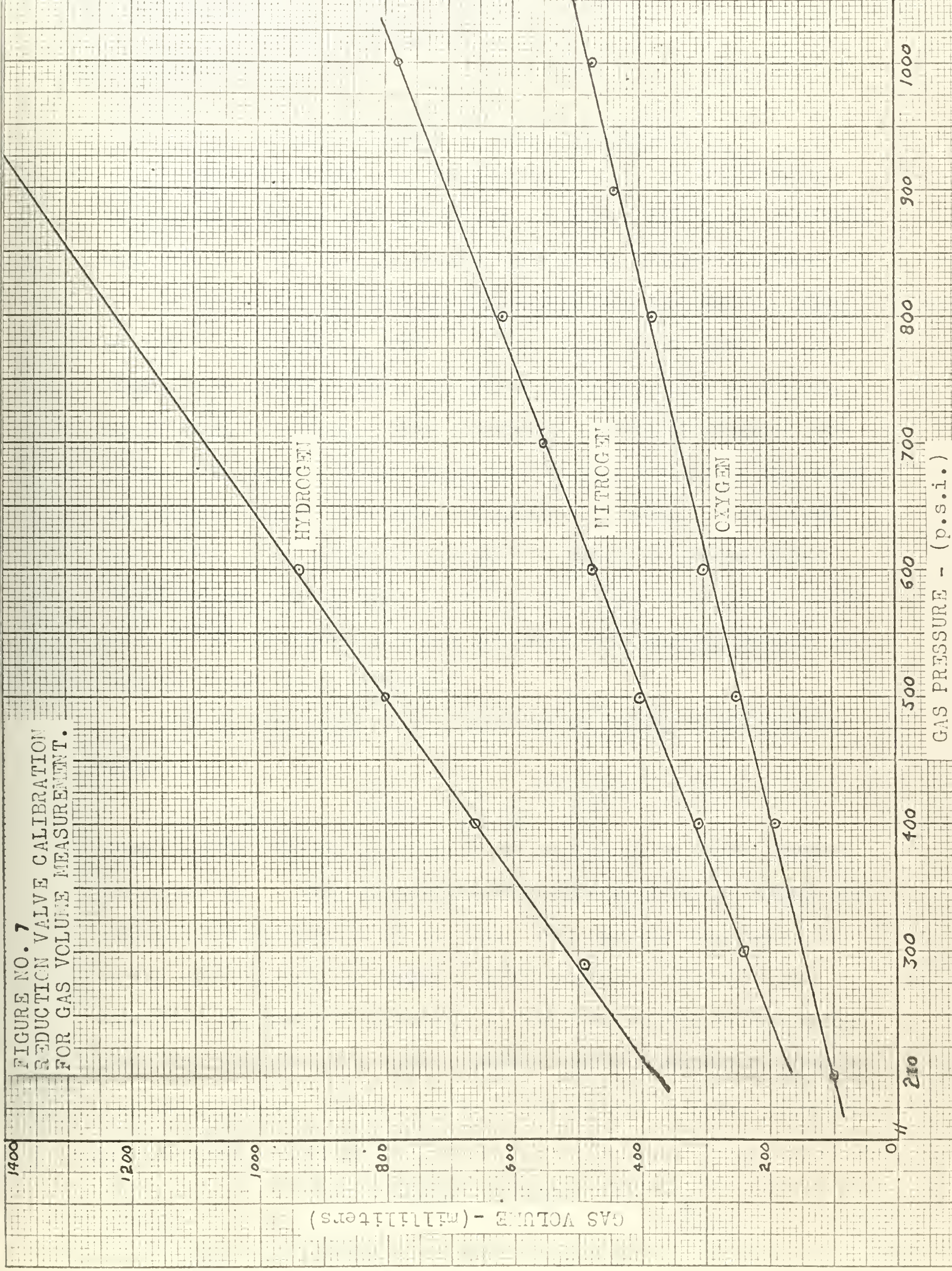


FIGURE NO. 7
REDUCTION VALVE CALIBRATION
FOR GAS VOLUME MEASUREMENT.

APPENDIX II

SAMPLING TECHNIQUE AND ENERGY COMPUTATION

As mentioned in the text and other appendices, the wave forms of the explosive signals were displayed on the Hughes Memo-scope. Ordinates were then recorded every Δt seconds where Δt is defined as follows:

If any complex wave form be sampled at a rate such that the number of samples is $2TW+1$, where T is the length of the signal if the signal is non-periodic and is the period if the signal has periodicity and where W is defined as twice the highest significant frequency component, then sampling theory states that the wave form may be reproduced from these ordinates to an excellent degree of accuracy. If we assume that $2TW$ is much greater than one then the number of samples becomes $2TW$ and the sampling interval is T, the length of the pulse, divided by $2TW$, the number of sample ordinates; this sampling interval is that Δt which was to be defined.

From sampling theory we also know that the energy in the pulse is given by

$$\text{Energy} = \sum V_k^2 \cdot \Delta t$$

where $\sum V_k^2$ is the summation of the squares of the several sampled ordinates, V_k. Here the waveform is assumed to be one of voltage and also to be taken across a one ohm load. From the gain characteristics of the tape recorder, the response characteristics of the receiving hydrophone and spherical divergence for the known spacing between hydrophone and transducer, the voltage ordinates may be converted to acoustic pressure ordinates. Acoustic energy in the explosive pressure pulse may then be computed from the relation -

$$\text{Energy} = \frac{4\pi \cdot \Delta t}{\rho c} \sum P_k^2$$

where $\sum P_k^2$ is the summation of the squares of the pressure ordinates, P_k. The quantity ρc is the acoustic impedance of sea water and the term 4π serves to integrate over the standard sphere of one meter radius. Here it is assured that there is no directivity, an assumption that is reasonable for the frequencies involved and one that was to some degree verified by observation.

Now, compute the conversion constant which converts voltage squared to acoustic pressure squared. Assume one volt out of the tape recorder at a microphone input level setting of four (24 db gain). The input would then be 24 db below one volt; and, assuming the receiving hydrophone to be flat at -85 db re 1 volt per microbar, the sound pressure level at 20 ft is

$$\text{SPL} = -24 - (-85) = 61 \text{ db.}$$

Allowing for spherical divergence to find the source level (SL).

$$\text{SL} = 61 + 20 \log r \qquad (r \text{ in meters.})$$

$$\text{SL} = 61 + 20 \log 6.10 = 76.7 \text{ db.}$$

From the relation between source level and pressure

$$\text{SL} = 20 \log 10\, P_4 \qquad \text{(where } P_4 \text{ is acoustic pressure in Newtons per square meter.)}$$

The pressure equivalent of 1 volt is

$$P_4 = 684 \text{ Newtons/meters}^2\text{/volt.}$$

squaring this constant yields

$$P_4^2 = 4.68 \times 10^5 \text{ Newtons}^2\text{/meters}^4\text{/volts}^2.$$

Similar calculations for microphone input levels of three (12 db gain) and three and one-half (18 db gain) gave as values for P^2 and P

$$P_3^2 = 7.41 \times 10^6 \text{ Newtons}^2\text{/meters}^4\text{/volts}^2.$$

$$P_3 = 2.725 \times 10^3 \text{ Newtons/meters}^2\text{/volt.}$$

$$P_{3.5}^2 = 1.870 \times 10^6 \text{ Newtons}^2\text{/meters}^4\text{/volts}^2.$$

$$P_{3.5} = 1.368 \times 10^3 \text{ Newtons/meters}^2\text{/volt.}$$

so for any given $\sum V_k^2$ and microphone input level the energy in the pulse is

$$\text{Energy} = \frac{4\pi \cdot \Delta t}{\rho c} P_{\text{mic Level}}^2 \sum V_k^2$$

and the instantaneous peak power is

$$\text{Peak power} = \frac{4\pi P_{\text{mic level}}^2}{\rho c} \cdot V_{\text{peak}}^2$$

A tabulation for all shots is given in Appendix III.

APPENDIX III

A TABULATION OF ALL SHOTS, TIME DOMAIN PHOTOGRAPHS AND FREQUENCY SPECTRA

This appendix is a tabulation of all shots. Table I includes shot number, date shot made, nature and quantity of excess gas, instantaneous peak acoustic power and total acoustic energy. Time domain photographs and frequency spectra for each shot in Table I are also shown.

In the time domain photographs the ordinate is given in newtons/meter^2 per division and the abscissa in milli-seconds per division. In the frequency spectra the ordinate is in decibels below the peak component and the abscissa in cycles per second.

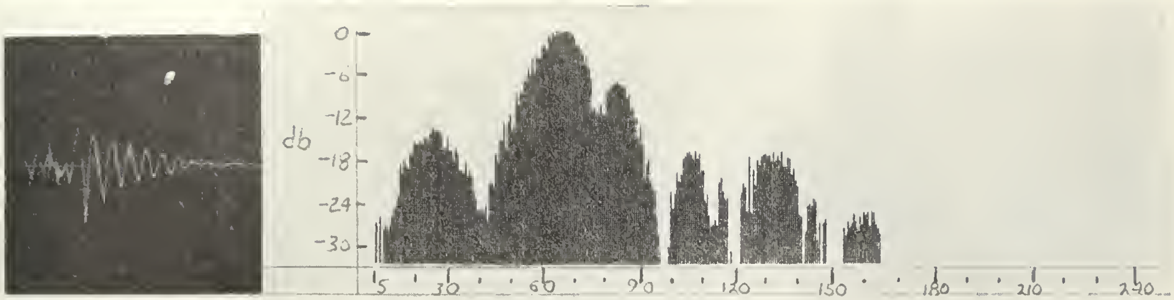
TABLE I

Shot	Date of Shot	Excess Gas H_2 Liters	Excess Gas N_2 Liters	Instantaneous Peak Acoustic Power Watts	Total Acoustic Energy Joules
1	21 Feb.	3.0	-	5.5	.051
2	7 Mar.	3.0	-	11	.093
3	7 Mar.	2.5	-	36.7	.248
4	13 Mar.	2.25	-	137	.458
5	23 Feb.	2.0	-	88	.580
6	7 Mar	2.0	-	107	.562
7	13 Mar.	1.75	-	146	.690
8	7 Mar.	1.5	-	137	.612
9	13 Mar.	1.5	-	146	.647
10	13 Mar.	1.25	-	208.5	.544
11	28 Feb	1.0	-	55.3	.196
12	21 Feb.	-	3.0	11.7	.066
13	7 Mar.	-	3.0	12.4	.138
14	7 Mar.	-	2.5	8.6	.136
15	27 Mar.	-	2.0	23.0	.125
16	13 Mar.	-	2.0	29.9	.252
17	13 Mar.	-	1.75	91.6	.471
18	7 Mar.	-	1.5	95	.511
19	13 Mar.	-	1.5	87.6	.509
20	13 Mar.	-	1.25	156	.518
21	28 Feb.	-	1.0	55.3	.212

TABLE I (cont.)

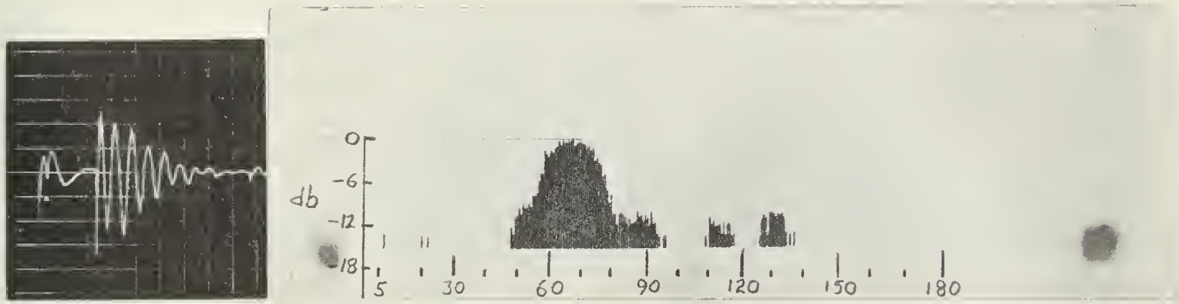
Shot	Date of Shot	Excess Gas H_2	O_2	N_2	Instantaneous Peak Acoustic Power	Total Acoustic Energy
		Liters	Liters	Liters	Watts	Joules
22	7 Mar.	0.5	-	0.5	40.6	.049
23	7 Mar.	1.0	-	0.5	102.7	.359
24	7 Mar.	0.5	-	1.0	146.8	.469
25	7 Mar.	1.5	-	0.5	74	.514
26	28 Feb.	1.0	-	1.0	55.3	.442
27	28 Feb.	0.5	-	1.5	39.3	.283
28	7 Mar.	2.0	-	0.5	21.2	.177
29	7 Mar.	1.5	-	1.0	11.75	.118
30	7 Mar.	1.0	-	1.5	59.5	.130
31	7 Mar.	0.5	-	2.0	13.8	.177
32	7 Mar.	2.5	-	.5	8.34	.135
33	7 Mar.	2.0	-	1.0	9.82	.133
34	7 Mar.	1.5	-	1.5	8.02	.120
35	28 Feb.	1.0	-	2.0	13.8	.154
36	28 Feb.	0.5	-	2.5	11.1	.074
37	28 Feb.	-	0.5	1.5	52.4	.260
38	28 Feb.	-	0.5	2.5	9.82	.108
39	28 Feb.	-	1.0	1.0	55.3	.198
40	28 Feb.	-	1.0	2.0	6.46	.074
41	27 Feb.	-	3.0	-	9.82	.073
42	21 Feb.	-	-	-	-	-

Note: All shots contain 0.67 liter H_2 and 0.33 liter O_2 in addition to excess shown. Shot number 42 not sampled.



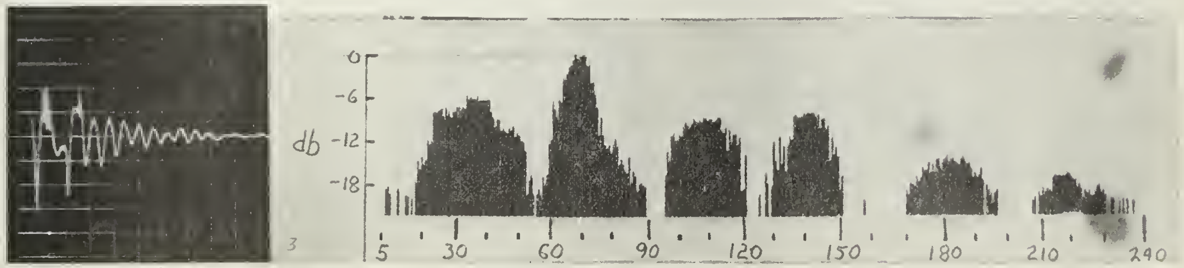
20 m.sec/div.
342 newtons/m^2/div.

frequency-(cps(
SHOT NO. 1



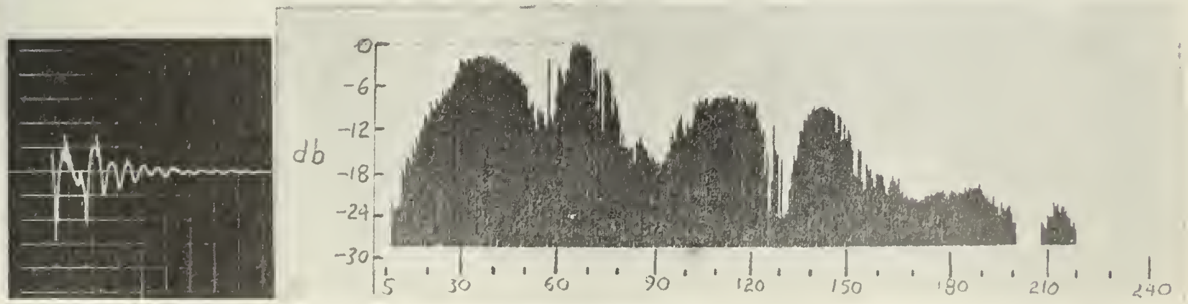
20 m.sec/div.
342 newtons/m^2/div.

frequency-(cps)
SHOT NO. 2



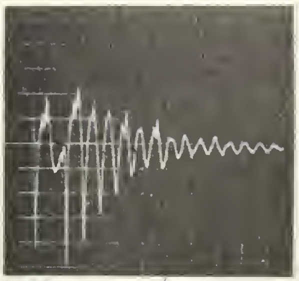
20 m.sec/div.
684 newtons/m^2/div.

frequency-(cps)
SHOT NO. 3

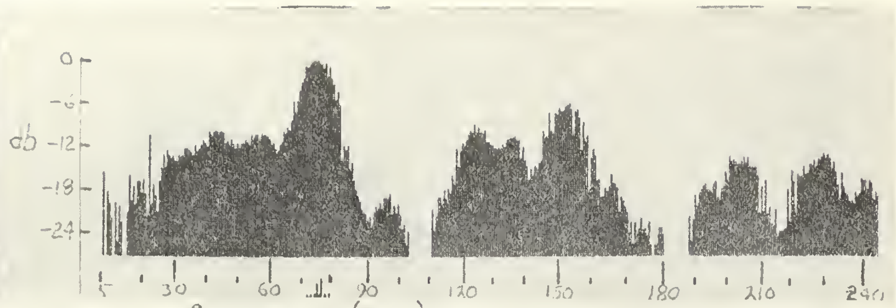


20 m.sec/div.
1368 newtons/m^2/div.

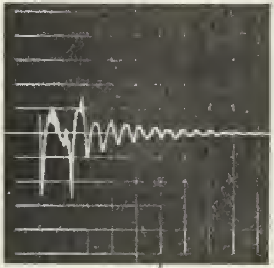
frequency-(cps)
SHOT NO. 4



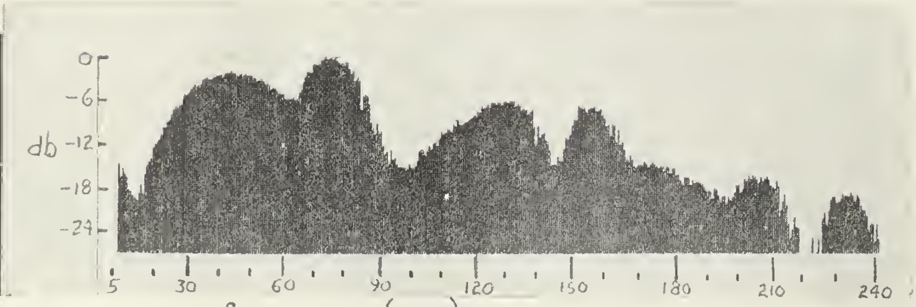
20 m.sec/div.
684 newtons/m²/div.



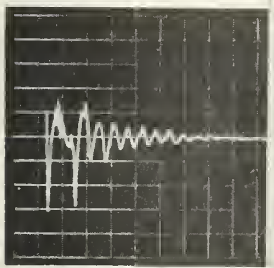
SHOT NO. 5



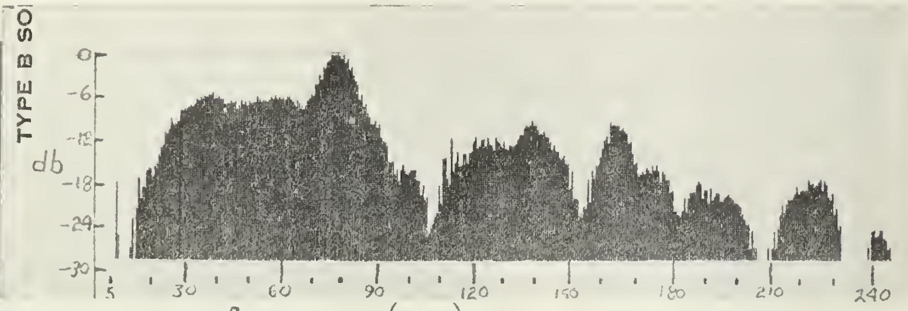
20 m.sec/div.
1368 newtons/m²/div.



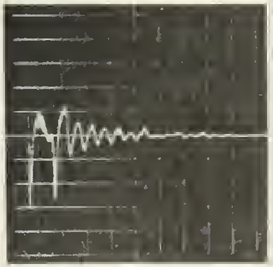
SHOT NO. 6



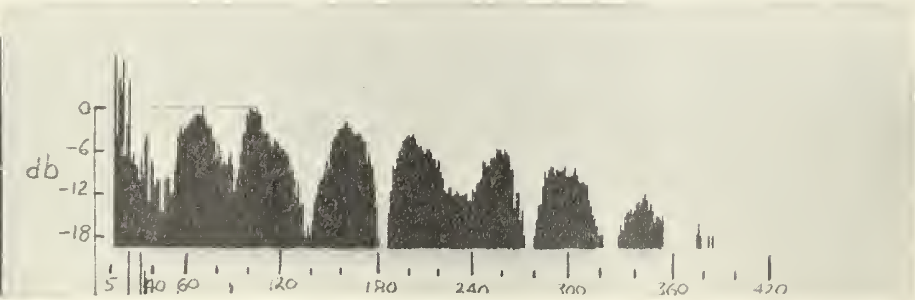
20 m.sec/div.
1368 newtons/m²/div.



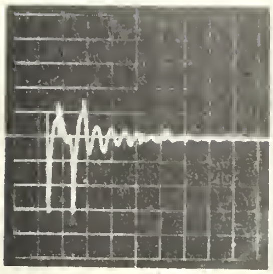
SHOT NO. 7



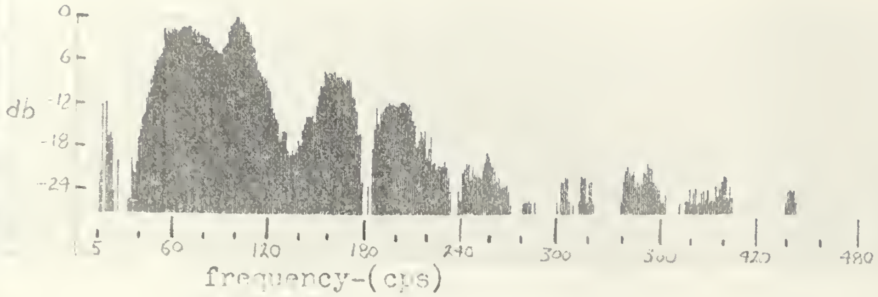
20 m.sec/div.
1368 newtons/m²/div.



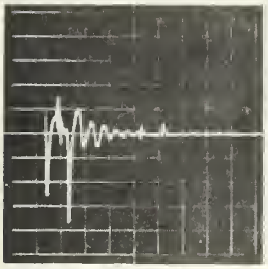
SHOT NO. 8



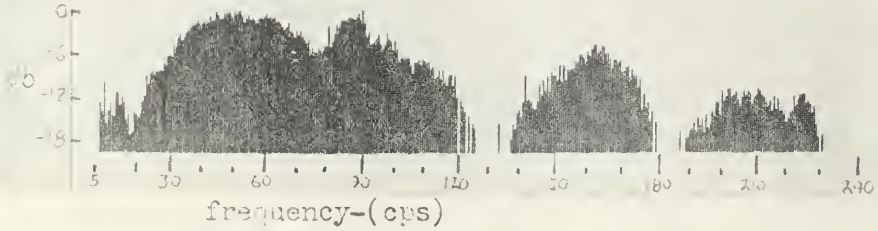
20 m.sec/div.
1368 newtons/m²/div.



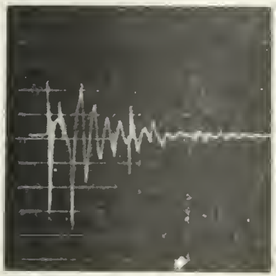
SHOT NO. 9



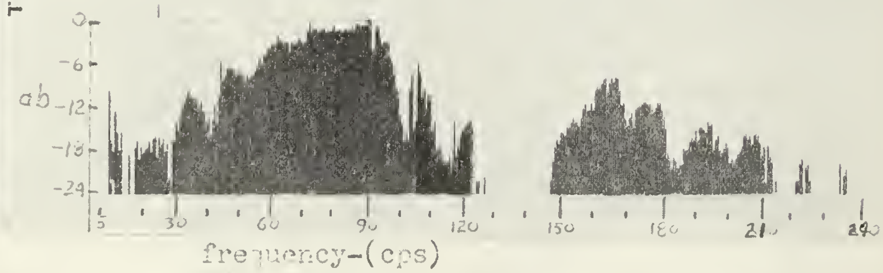
20 m.sec/div.
1368 newtons/m²/div.



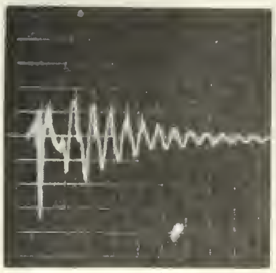
SHOT NO. 10



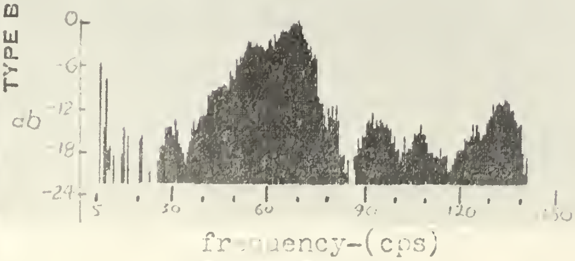
20 m.sec/div.
684 newtons/m²/div.



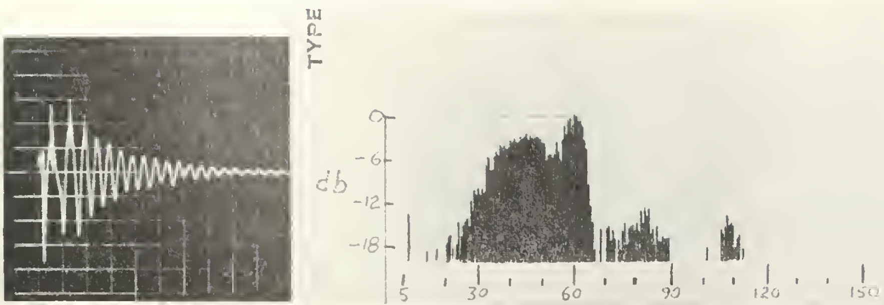
SHOT NO. 11



20 m.sec/div.
342 newtons/m²/div.

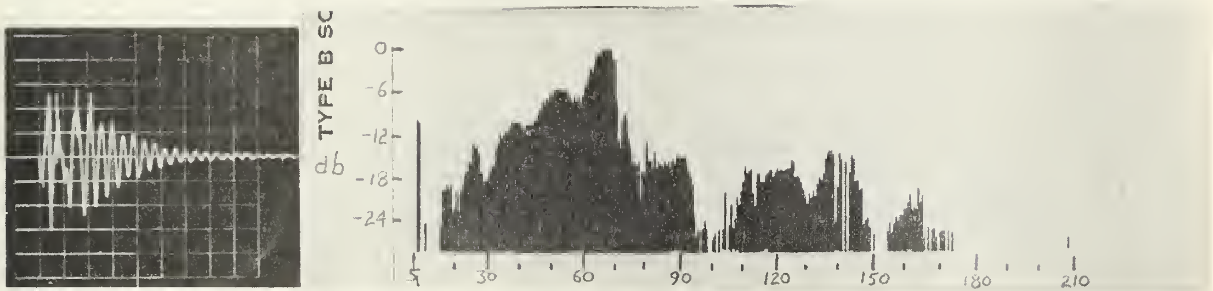


SHOT NO. 12



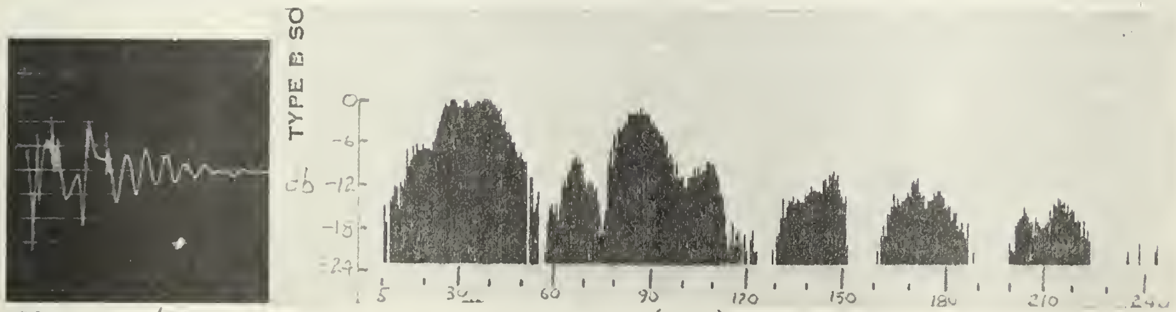
30 m.sec/div.
342 newtons/m^2/div.

frequency-(cps)
SHOT NO. 13



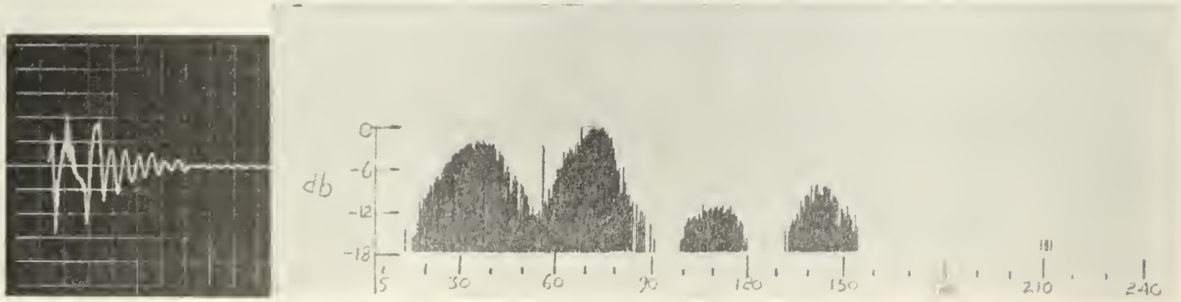
20 m.sec/div.
342 newtons/m^2/div.

frequency-(cps)
SHOT NO. 14



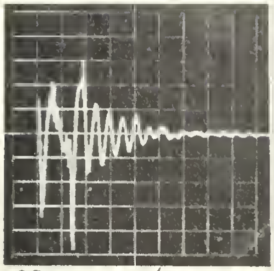
20 m.sec/div.
342 newtons/m^2/div.

frequency-(cps)
SHOT NO. 15

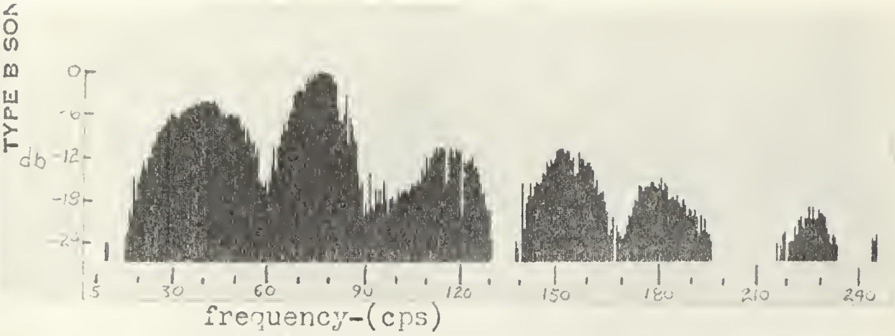


20 m.sec/div.
684 newtons/m^2/div.

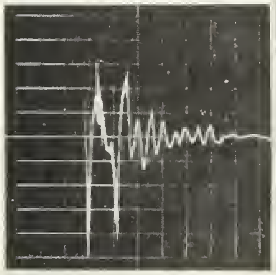
frequency-(cps)
SHOT NO. 16



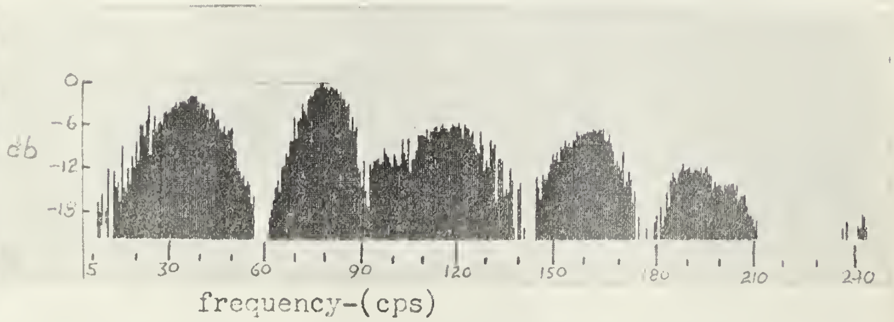
20 m.sec/div.
684 newtons/m^2/div.



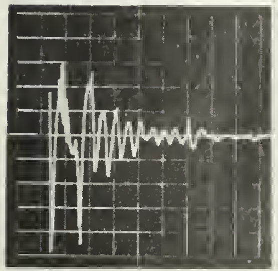
SHOT NO. 17



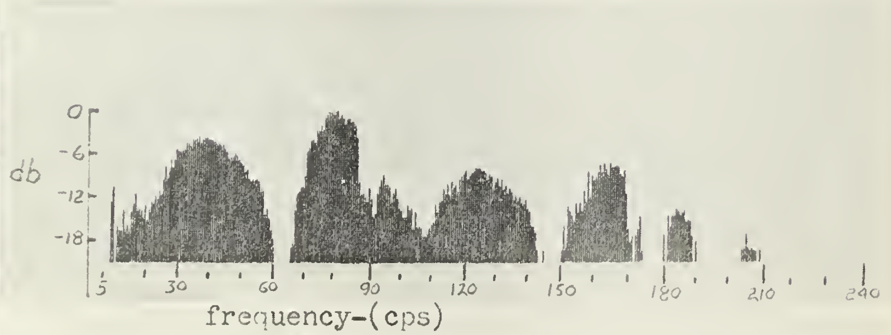
20 m.sec/div.
684 newtons/m^2/div.



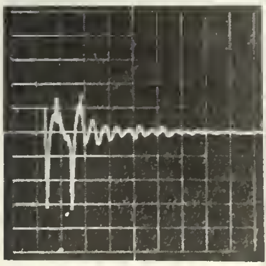
SHOT NO. 18



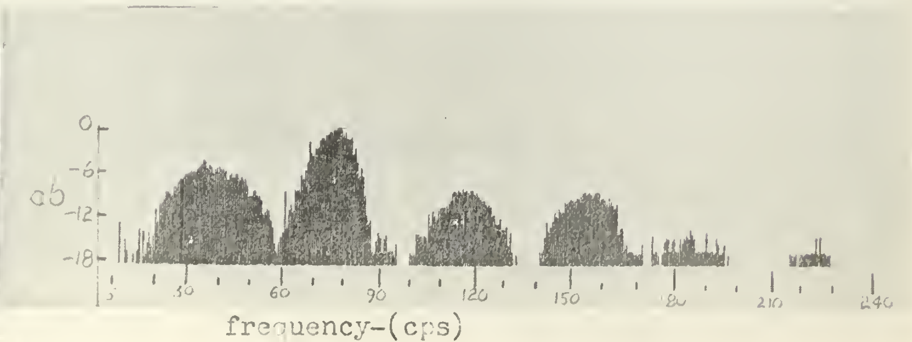
20 m.sec/div.
684 newtons/m^2/div.



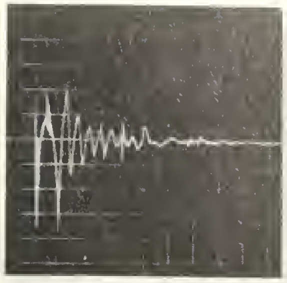
SHOT NO. 19



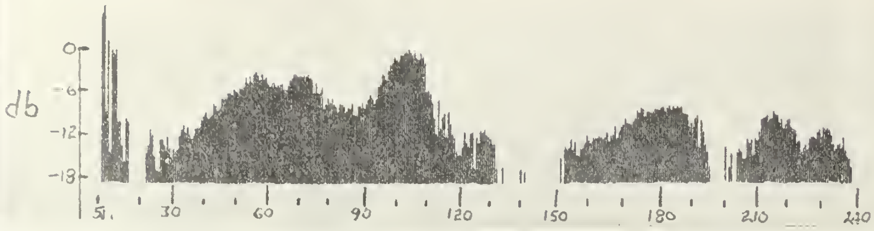
20 m.sec/div.
1368 newtons/m^2/div.



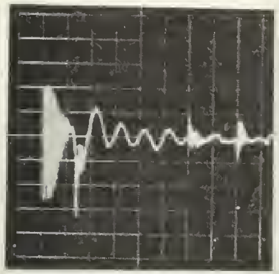
SHOT NO. 20



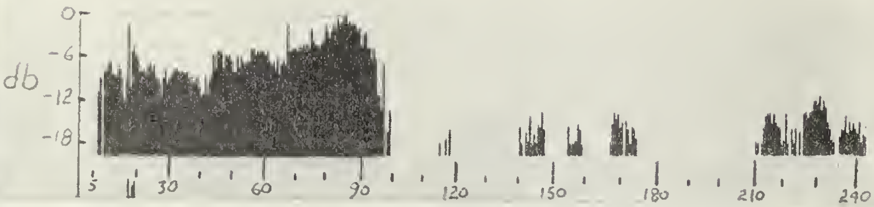
20 m.sec/div.
684 newtons/m²/div.



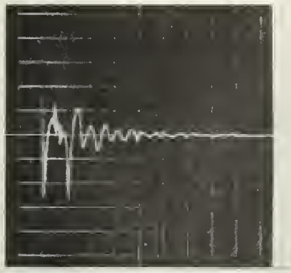
frequency-(cps)
SHOT NO. 21



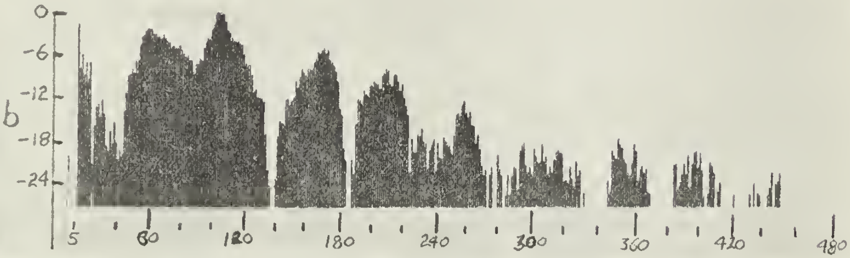
10 m.sec/div.
684 newtons/m²/div.



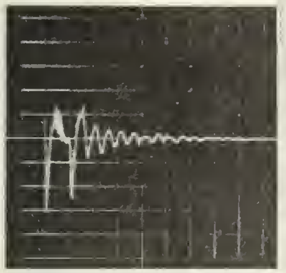
frequency-(cps)
SHOT NO. 22



20 m.sec/div.
1368 newtons/m²/div.



frequency-(cps)
SHOT NO. 23



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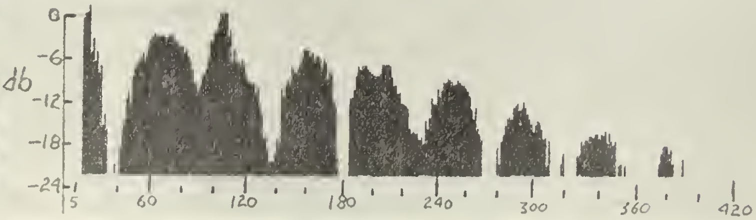
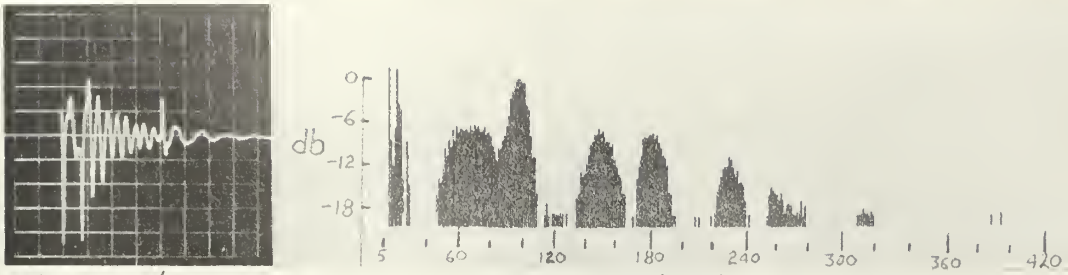
ECTRIC CO.



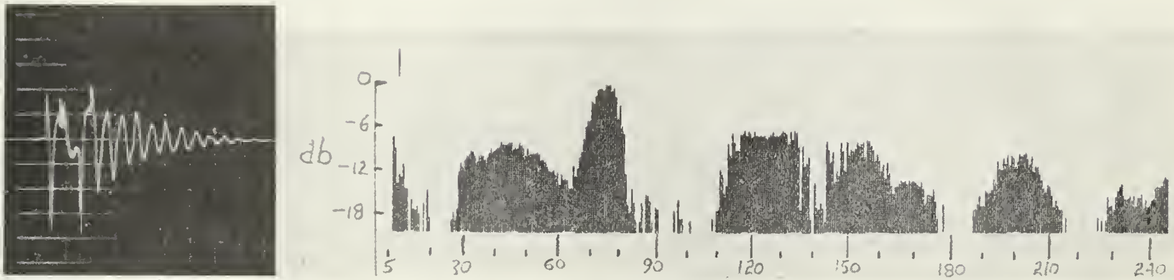
20 m.sec/div.
1368 newtons/m²/div.

frequency-(cps)
SHOT NO. 24



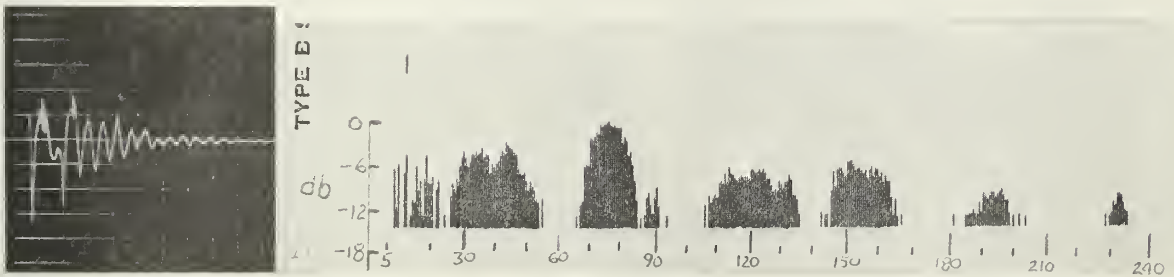
30 m.sec/div.
684 newtons/m^2/div.

frequency-(cps)
SHOT NO. 25



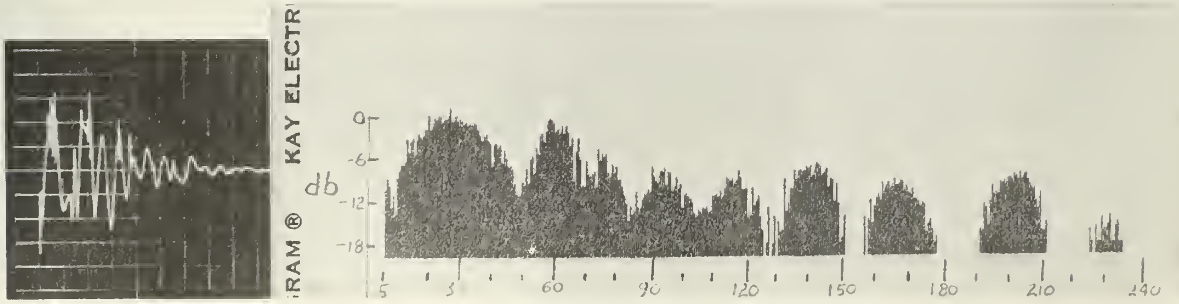
20 m.sec/div.
684 newtons/m^2/div.

frequency-(cps)
SHOT NO. 26



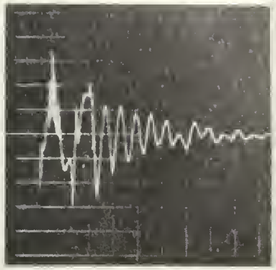
20 m.sec/div.
684 newtons/m^2/div.

frequency-(cps)
SHOT NO. 27

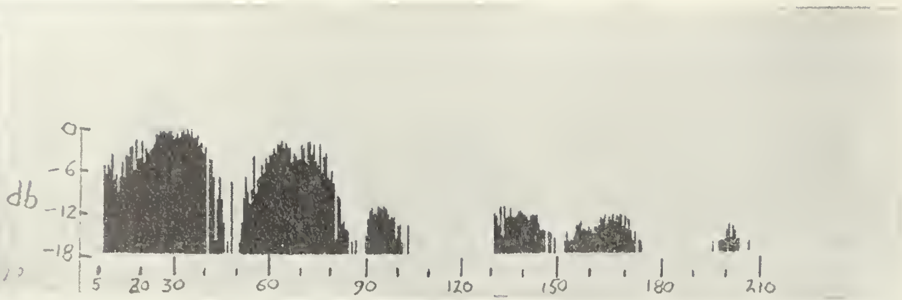


20 m.sec/div.
342 newtons/m^2/div.

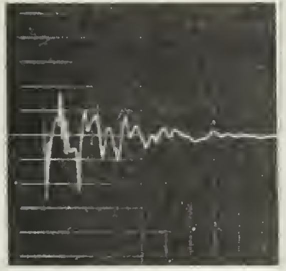
frequency-(cps)
SHOT NO. 28



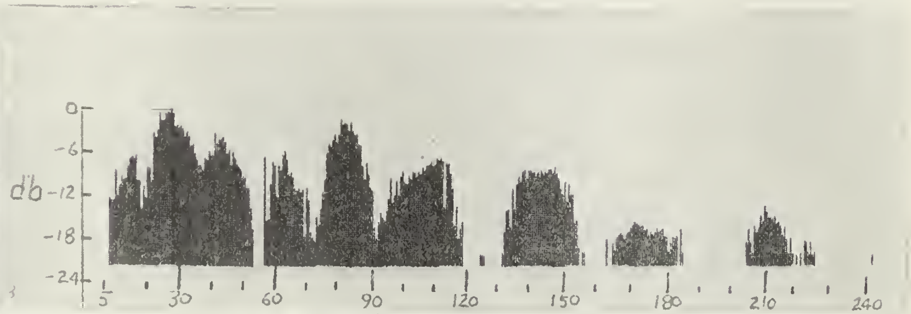
20 m.sec/div.
342 newtons/m^2/div.



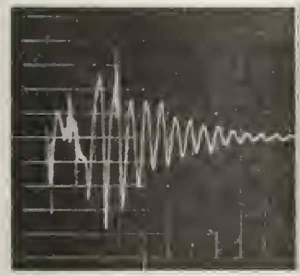
frequency-(cps)
SHOT NO. 29



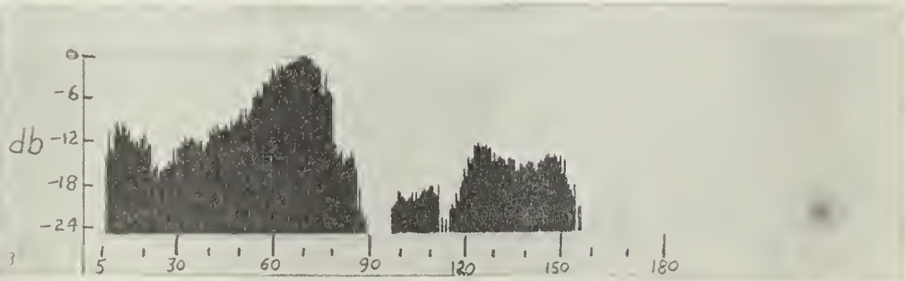
20 m.sec/div.
684 newtons/m^2/div.



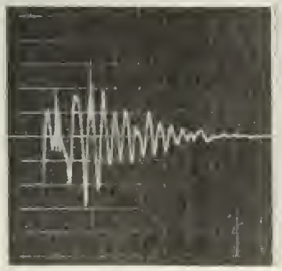
frequency-(cps)
SHOT NO. 30



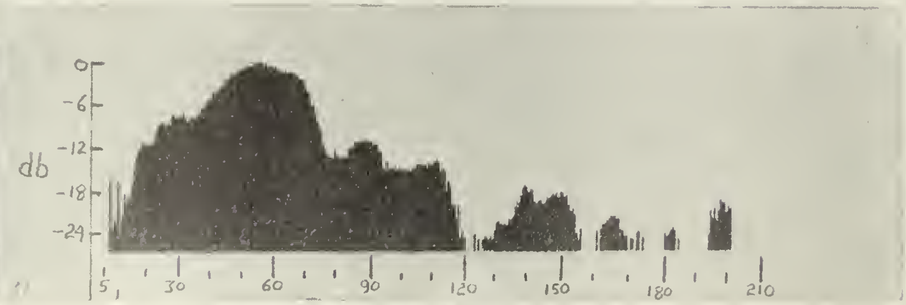
20 m.sec/div.
342 newtons/m^2/div.



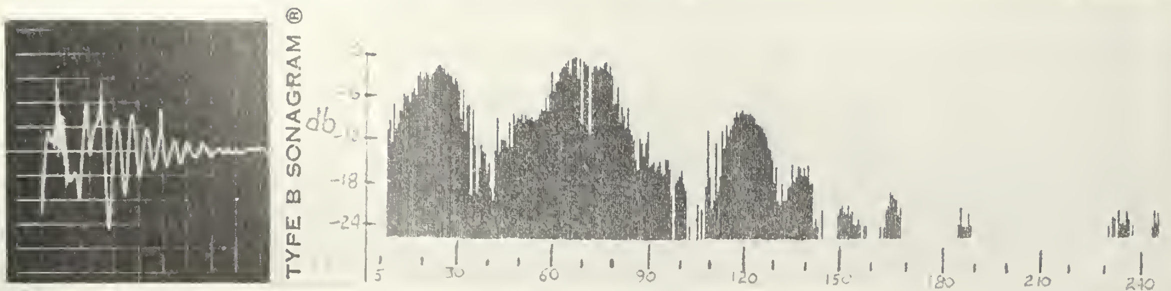
frequency-(cps)
SHOT NO. 31



30 m.sec/div.
[illegible] newtons/m^2/div.

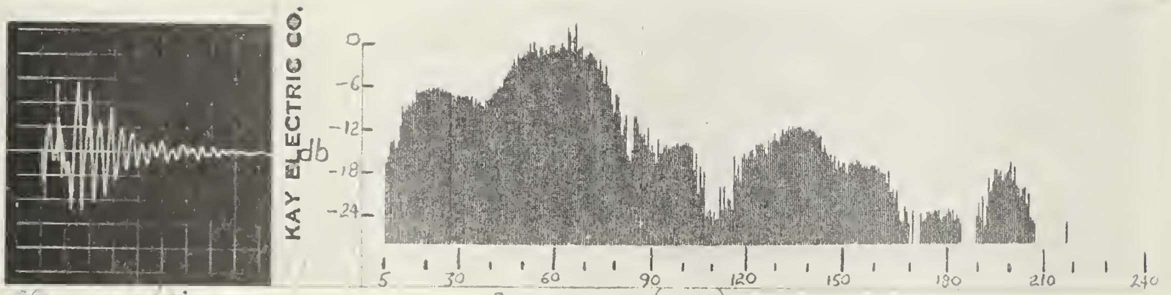


frequency-(cps)
SHOT NO. 32



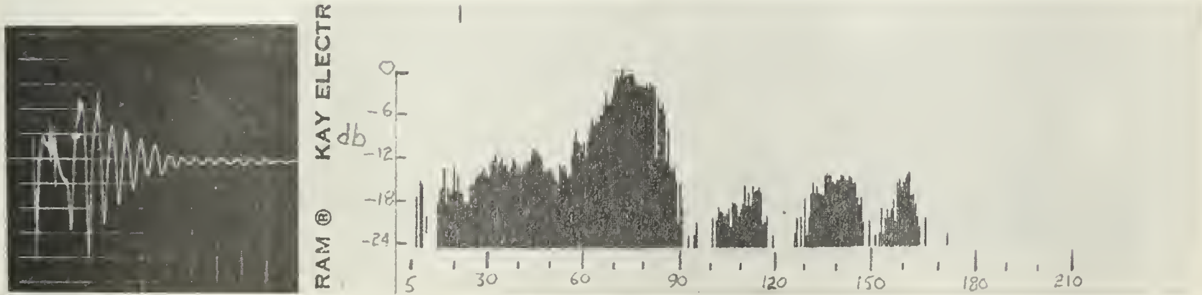
20 m.sec/div.
342 newtons/m^2/div.

frequency-(cps)
SHOT NO. 33



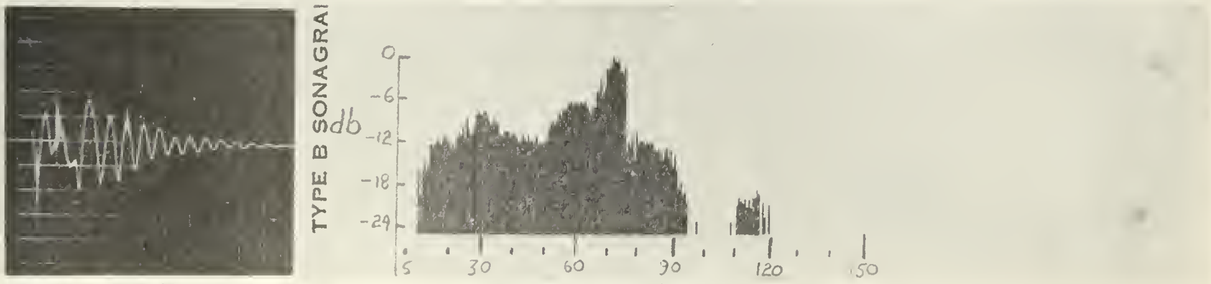
20 m.sec/div.
342 newtons/m^2/div.

frequency-(cps)
SHOT NO. 34



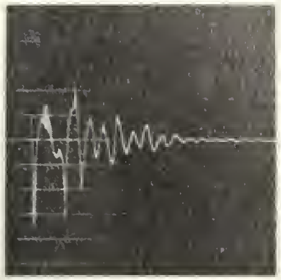
20 m.sec/div.
342 newtons/m^2/div.

frequency-(cps)
SHOT NO. 35

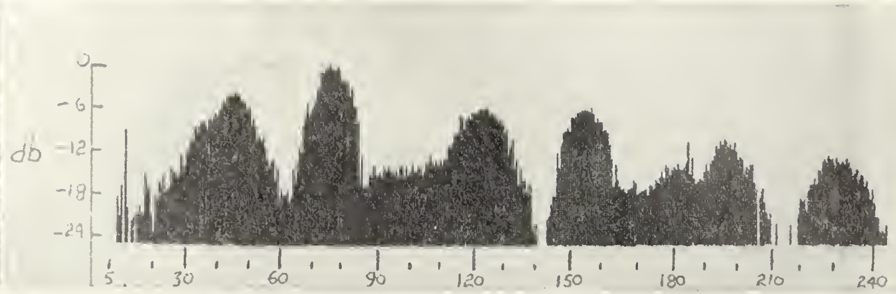


20 m.sec/div.
342 newtons/m^2/div.

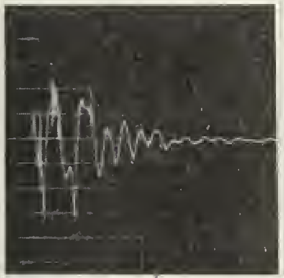
frequency-(cps)
SHOT NO. 36



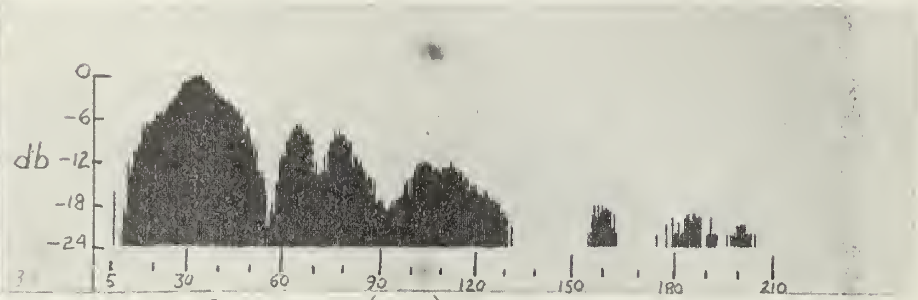
20 m.sec/div.
684 newtons/m^2/div.



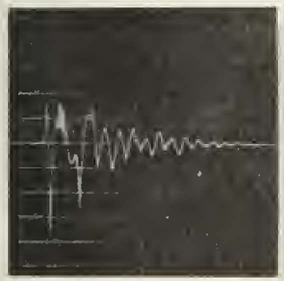
SHOT NO. 37



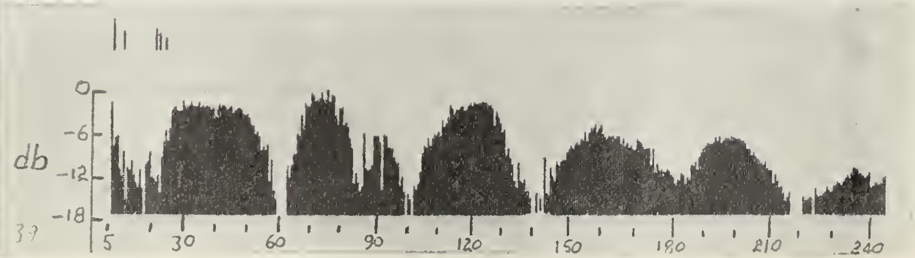
20 m.sec/div.
342 newtons/m^2/div.



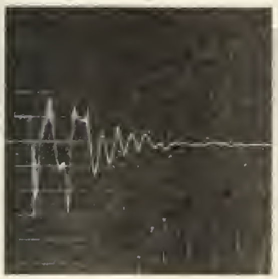
SHOT NO. 38



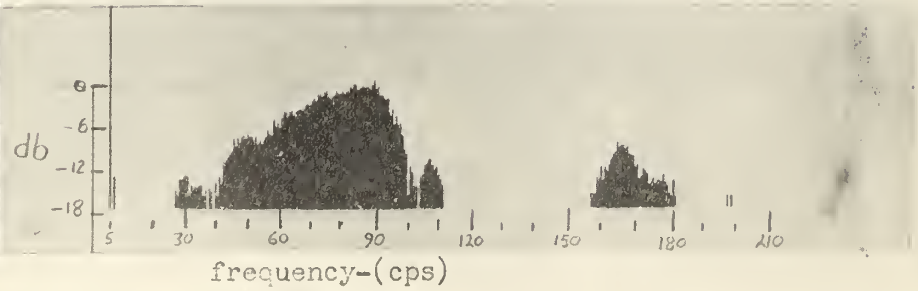
20 m.sec/div.
684 newtons/m^2/div.



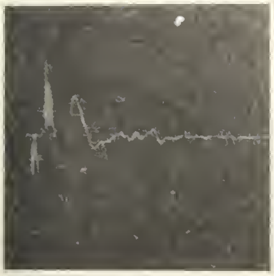
SHOT NO. 39



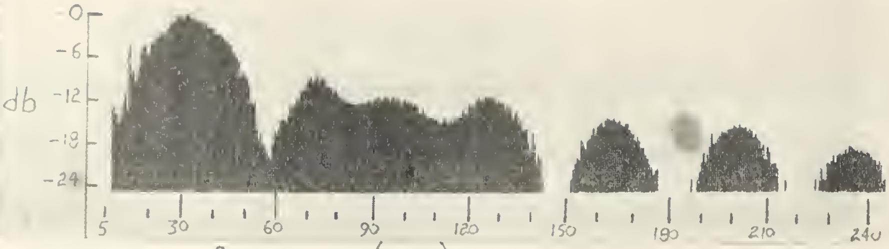
20 m.sec/div.
342 newtons/m^2/div.



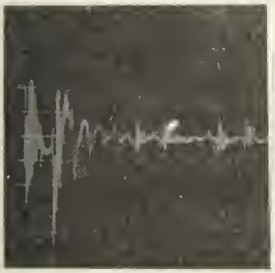
SHOT NO. 40



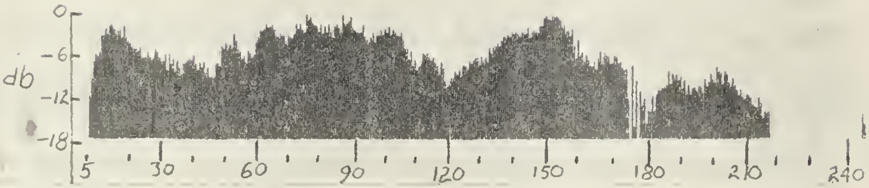
20 m.sec/div.
342 newtons/m^2/div.



frequency-(cps)
SHOT NO. 41



10 m.sec/div.
684 newtons/m^2/div.



frequency-(cps)
SHOT NO. 42

APPENDIX IV

CALCULATION OF CHEMICAL ENERGY

Here it is assumed that the recombination of the hydrogen and oxygen takes place in such a manner that gaseous water is formed initially and that the heat of combustion of this reaction is the available chemical energy. The reaction is:

$$H_2 + \frac{1}{2} O_2 = H_2O + Q$$

where Q is the heat of combustion in cal./mole and is equal to 57,800 cal/mole.

One liter of combustible mixture (0.33 O_2 and 0.67 H_2) was maintained. Assuming that hydrogen and oxygen are ideal gases (22.4 liters/mole), there is 0.0299 mole of hydrogen and 0.0149 moles of oxygen. The reaction will yield 0.0299 moles of water vapor and 1728 calories of heat. Converting calories to joules gives 7260 joules. The value of 7260 joules was used as the chemical energy in computing the chemical to acoustic energy conversion efficiencies.

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